

## APPENDIX B

### REVIEW OF MEASUREMENT AND TESTING PROBLEMS<sup>\*</sup>

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#### APPARATUS AND RELATED PROCEDURE

##### Background

Teledyne Continental Motors experience with the measurement of exhaust emissions from aircraft piston engines goes back to the latter part of 1971 when five engines of each of four different models were tested under contract to the Environmental Protection Agency. Additional testing was accomplished in late 1971 and early 1972 on an inhouse program to evaluate the emissions of an exhaust-air-injected, turbocharged engine.

Subsequently, a contract was awarded on June 28, 1974, which was jointly funded by both the FAA and NASA (DOT FA74NA-1091).

This review of measurement and testing problems presents an overview of work in this area from the beginning of the FAA contract.

##### Exhaust Emissions Measurement Equipment

Attachment I presents a concise list and description of problems encountered with the exhaust emissions measurement analyzers and the attendant sample handling systems.

The problems have been attributable mainly to emission analyzer durability and design. Some problems early in the contract were the result of the learning process. In effect all of the participants in the NAFEC Contract were required to custom make a total system package which would comply with the requirements of the Federal Register, Volume 38, Number 136, Part 87.93.

While equipment development continues and durability problems have not entirely been overcome, we believe that our present system is capable of being maintained in accordance with Part 87.

##### Testing Problems

Throughout the contract, testing problems have been encountered

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<sup>\*</sup>Material distributed but not presented at the Symposium.

which resulted in lack of data repeatability, both inhouse and between TCM and NAFEC. These repeatability problems stem basically from the fact that testing conditions were not and could not be held constant with current test cell equipment.

It was agreed that, for each operating mode, the controlled variables fuel flow, engine speed, manifold pressure, induction air inlet pressure, and engine cooling air pressure would be held to specified values. The variables leading to poor data repeatability which were recorded but not controlled were induction air and cooling air temperatures, induction air humidity, and exhaust back-pressure. These lead to variations in engine power, cylinder head temperature, induction air flow and, most importantly, emissions.

In addition, the specification of the amount of cooling air pressure to be supplied being fixed at a constant value does not lend itself to sound judgmental values of cylinder head overtemperature safety limits. The question continually arose as to the expected variability of these safety limits in a variety of actual airframe installations. The matter was considered important enough to be investigated under a supplement to the Phase I contract in the form of a flight test program.

It is clear at this point in time that more satisfactory, repeatable results would have been obtained had the uncontrolled variables been controlled. Since, to date, no universal correction factors are available to account for variations in emissions due to humidity, temperature, and pressure of induction air, it is apparent that future testing of this sort should include requirements aimed at maintaining the induction air inlet conditions to a set of some, yet unspecified, standard atmospheric conditions.

#### Engine-Related Problems

During the course of the NAFEC contract, TCM has tested five engines ranging in horsepower from 100 to 435. These engines vary in complexity from the simple O-200-A, a carbureted engine with a fixed pitch propeller, to the highly complex GTSIO-520-K, which is geared, turbocharged, fuel injected, intercooled, and has sonic venturi bleed air provisions for cabin pressurization.

The basic problem to which the contract terms addressed themselves was a matter of how to measure emissions for all these engines on a common basis so that the results would be comparable. This involved selecting various parameters for each individual engine which would comply with both the intended airframe requirements on the one hand and consistency with contract goals on the other. As a result, the contract specifications had to be reevaluated and changed to accommodate the variations among the five engines as experience was gained on the emissions test stand. Still, it cannot be said that every engine was treated on an

equal basis with the others.

As an example, the O-200-A engine was operated at the same conditions for takeoff and climb modes as is normal for that engine. The GTSIO-520-K, however, which has a 5-minute takeoff rating at full power was operated at 80 percent power, 90 percent speed in the climb mode. The O-200-A, which was equipped with a typical fixed-pitch flight prop, could not develop full power (full rpm) in the static test stand condition, whereas the remaining four engines were equipped with constant speed propellers allowing prop governor adjustments so that full rpm could be attained.

All TCM engines are designed to operate most efficiently at the higher power modes. While the engines would idle satisfactorily for long periods of time, the inappropriate valve and spark timing and induction system characteristics caused widely variable exhaust emissions values to be measured in this mode of operation. As a consequence a large degree of data scatter was observed and poor repeatability resulted.

#### Air Flow Measurement

In addition to the exhaust emissions measurement equipment problems discussed previously, there was little reason to suspect any difficulties with our engine operating parameter measurements. Initially in the program when testing the O-200-A engine, an airflow measurement device was used that later was suspected to be inaccurate due to data reduction result crosschecks. The valve device was replaced with a modern laminar flowmeter which is compensated for pressure and temperature. Subsequent cross-calibration with other devices including a gas flowmeter, a sharp-edged orifice, a calibrated laminar flow standard, and two turbine-type flowmeters have shown the laminar flowmeter to be the most accurate single device covering the widest range of engine airflow requirements.

Retest of the O-200-A has been accomplished using the laminar flowmeter.

#### Summary

While the phase I contract completion date has been extended by additions to the work plan to gather more data, the principal reason for delays beyond the initial phase I completion date of September 1, 1975, has been attributable to long periods of inactivity because of exhaust emissions measurement equipment durability problems and delays due to the additional effort involved in sorting out these and other problems with the measurement system.

Systematic checks and calibrations of the instrumentation have reduced the above measurement and testing problems to a minimum. The data presented in this report are considered representative of the engines

tested. Absolute values may differ from facility to facility, but in no instance has this difference changed the trends or conclusions presented herein.

## EXHAUST EMISSIONS CALCULATION PROCEDURE

### Background

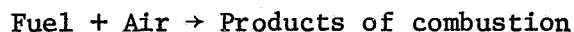
The Federal Register, Volume 38, Number 136, Part II, dated July 17, 1973, sets forth the requirements for the control of air pollution from all aircraft and aircraft engines. Subparts E and I and appendix B deal with the requirements for compliance with the law regarding exhaust emissions from aircraft piston engines.

The exhaust emission test is designed to measure hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen ( $\text{NO}_x$ ) concentrations (percent or parts per million by volume) and determine mass emissions through calculations during a simulated aircraft landing-takeoff (LTO) cycle.

The calculations required to convert exhaust emission concentrations (raw emissions measurements) into mass emissions are the subject of this discussion.

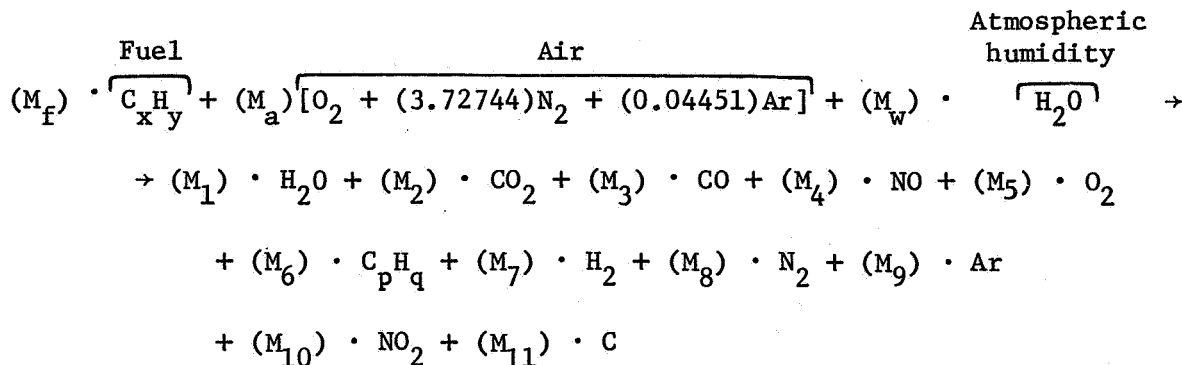
### Combustion Equation

The chemical equation for the combustion of a hydrocarbon fuel in air can be represented symbolically by



To be able to deal mathematically with the combustion equation it must be written in a form such that the coefficients, representing the quantities of each constituent, are known by virtue of measurement or are calculable using the principles of mass conservation or chemical equilibrium.

The combustion equation used as the basis for the emissions calculations is



where

$M_i$	number of lbm-moles of $i^{\text{th}}$ constituent; 1 lbm-mole (lb-mass mole) of a substance is quantity of that substance in pounds-mass (numerically equal to the molecular weight of substance in atomic mass units): 1 lbm-mole of water ( $\text{H}_2\text{O}$ ), therefore, would have mass of $(2)(1.008) + 16 = 18.016$ lbm
$\text{C}_x \text{H}_y$	pure hydrocarbon fuel containing $x$ atoms of carbon and $y$ atoms of hydrogen in each molecule
$\text{O}_2$	oxygen
$\text{N}_2$	nitrogen
Ar	argon
$\text{H}_2\text{O}$	water (vapor)
$\text{CO}_2$	carbon dioxide
CO	carbon monoxide
NO	nitric oxide
$\text{NO}_2$	nitrogen dioxide
$\text{C}_p \text{H}_q$	unburned hydrocarbon exhaust product containing $p$ atoms of carbon and $q$ atoms of hydrogen in each molecule
$\text{H}_2$	hydrogen
C	solid carbon

Examining each constituent of the equation, it is necessary to determine what can be measured, what can be calculated, and what assumptions must be made in order to calculate mass emissions values of HC, CO, and  $\text{NO}_x$ .

#### Fuel and Air

We have represented the fuel  $\text{C}_x \text{H}_y$  as a pure hydrocarbon molecule. In reality, gasoline is a blend of many hydrocarbon products of refined crude oil and contains, in addition, antiknock agents such as tetraethyl lead, deposit modifiers, antioxidants, detergents, antirust agents, dyes, and anti-icing agents which contain elements other than hydrogen and carbon. These other elements are ignored in the combustion equation as they are deemed negligible. The fuel molecule  $\text{C}_x \text{H}_y$  then is representative of a nominal or average hydrocarbon molecule with a ratio of hydrogen to carbon atoms of  $y/x$ . Although the actual values of  $y$  and  $x$

for the gasoline varies considerably and no specific values can be assigned to them in our simplified fuel molecule, the ratio of hydrogen to carbon atoms in 100/130 octane aviation gasoline can be measured and remains relatively constant at a value of about 2.125.

Likewise, the unburned hydrocarbon constituent in the exhaust may contain several species of hydrocarbons, but a ratio of  $q/p$  of 1.85 has been suggested to represent the average ratio of hydrogen to carbon in the exhaust hydrocarbon pollutant. This value, however, for the purpose of this analysis will be considered unknown.

The fuel flow is measured using a Cox Vortex Flowmeter, Model #4271.

At TCM, airflow is measured by a Merriam laminar flowmeter which gives a linear relationship between mass flow and pressure drop and compensates for temperature and pressure. The total mass flow measured includes the atmospheric humidity.

Humidity is calculated from measured values of wet and dry bulb temperatures and is given in terms of pounds-mass of water vapor per pound-mass of dry air.

#### Products of Combustion

The products of combustion as shown in the combustion equation are again simplified in that the nonhydrocarbon fuel additives are ignored.

The exhaust constituents which are measured include  $CO_2$ ,  $CO$ ,  $NO$ ,  $NO_2$ ,  $O_2$  and  $C H_q/p$ . The constituents which are known, a priori, are  $Ar$  and  $N_2$ . Those constituents which are not measured are  $C$ ,  $H_2$  and  $H_2O$ .

The formation of solid carbon  $C$  is the result of rich combustion of fuel (fuel burned in the presence of insufficient air) and to a varying extent, depending on engine age and condition, the burning of the oil lubricant entering the combustion chamber along the piston rings or valve guides. Chemical equilibrium calculations have shown that below fuel-air equivalence ratios of about 3.0 (fuel-air ratio of 0.20), solid carbon as a product of combustion is negligible compared to the remainder of the gaseous products. Aircraft piston engines do not normally run at overall equivalence ratios over 2.0 (fuel-air ratio of 0.13). The chemical equilibrium calculations, however, assume homogeneity of the fuel-air mixture. The lack of perfect mixture uniformity in a real engine would lead to some production of solid carbon due to localized rich mixtures within the combustion chamber.

At the present time solid carbon is not measured and is assumed for calculation purposes to be negligible. There is currently no equipment available to measure solid carbon production on a real-time basis.

Free hydrogen ( $H_2$ ), which is present in the exhaust products in

small but significant quantities, is also not measured. Real-time measurement equipment for  $H_2$  is available.

While there are systems on the market which will measure water ( $H_2O$ ) vapor content in the exhaust, they are expensive. Calculative procedures are available to estimate the quantity of water vapor in the exhaust.

Table B-1 outlines the equipment currently used by TCM to determine those exhaust products which are measured.

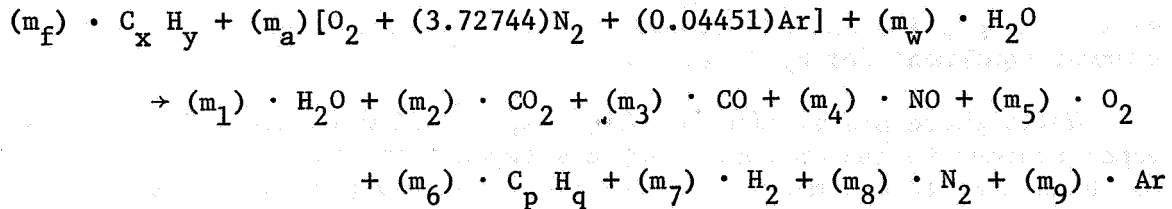
TABLE B-1

Exhaust product	Measuring instrument	Method used by measuring instrument
CO	Beckman Model 864 (NDIR)	Measurement of differential absorption of infrared light
CO <sub>2</sub>	Beckman Model 864 (NDIR)	Measurement of differential absorption of infrared light
NO, NO <sub>2</sub>	Beckman Model 951 H(CL)	$NO + O_3 \rightarrow NO_2 + \text{Light}$ ; measurement of light intensity due to reaction
O <sub>2</sub>	Scott Model 150	Measures effect of paramagnetic oxygen in gas sample on magnetic field
C <sub>p</sub> H <sub>q</sub>	Scott Model 215 (FID)	Measures effect on electrostatic field of ionized hydrogen and carbon from gas sample

#### Balancing Combustion Equation

By the principle of conservation of mass we know that the atomic quantities introduced into the engine induction system must also be present in the exhaust even though they are rearranged into different molecules by the combustion chemical reaction. Hence, all the carbon atoms entering the engine in the form of hydrocarbon fuel molecules must be present in the exhaust in the form of CO, CO<sub>2</sub>, and C<sub>p</sub> H<sub>q</sub>. This atom-balancing technique provides us with a system of equations by which we may solve for unknown quantities.

Going back to the original combustion equation, we eliminate solid carbon (C) and nitrogen dioxide (NO<sub>2</sub>) (it has been found that NO<sub>2</sub> does not exist in any significant quantity for our engines). We then divide each molar value on both sides of the equation by the sum of the molar values on the right side. The equation then becomes



where

$$m_i = \frac{M_i}{M_1 + M_2 + M_3 + M_4 + M_5 + M_6 + M_7 + M_8 + M_9}$$

Thus, every molar coefficient on the right side of the equation is now expressed in mole fractions such that

$$m_1 + m_2 + m_3 + m_4 + m_5 + m_6 + m_7 + m_8 + m_9 = 1.0$$

This is done for convenience and the reason for it will be demonstrated later.

The nine products of combustion represent an estimated 99.998 percent of the chemical composition of an equilibrium mixture at exhaust gas temperatures below 3000° R.

An oxygen balance results in

$$2m_a + m_w = m_1 + 2m_2 + m_3 + m_4 + 2m_5 \quad (1)$$

or

$$m_1 = 2m_a + m_w - 2m_2 - m_3 - m_4 - 2m_5$$

A carbon balance gives

$$x \cdot m_f = m_2 + m_3 + p \cdot m_6 \quad (2)$$

or

$$m_f = \frac{m_2 + m_3 + p \cdot m_6}{x}$$

Since our measurement of  $C_p H_q$  is in ppm carbon equivalent, we can represent  $C_p H_q$  as  $CH_{q/p}$ . Equation (2) then becomes

$$m_f = \frac{m_2 + m_3 + m_6}{x}$$



The remaining atomic balances are as follows:

$$\text{Hydrogen balance: } y \cdot m_f + 2m_w = 2m_1 + \frac{q}{p} m_6 + 2m_7 \quad (3)$$

$$\text{Nitrogen balance: } (3.72744)(2)m_a = m_4 + 2m_8 \quad (4)$$

$$\text{Argon balance: } (0.04451)m_a = m_9 \quad (5)$$

#### Water Correction Factor

Since  $\text{CO}$ ,  $\text{CO}_2$ , and  $\text{O}_2$  are measured on a dry volumetric basis (water vapor being removed from the exhaust sample before measurement) and  $\text{HC}$  and  $\text{NO}$  are measured on a wet volumetric basis, we must determine the amount of water vapor removed from the dry sample in order to correct all measured values to either a dry or a wet volumetric basis for calculative purposes. In doing this we are solving for one of the unknowns -  $m_1$  ( $\text{H}_2\text{O}$ ).

We can define the fuel to dry air mass ratio as

$$\frac{f}{A} = \frac{m_f(12.011x + 1.008y)}{m_a(138.2689)} \quad (6)$$

where

$$(12.011x + 1.008y) = \text{fuel molecular weight}$$

and

$$138.2689 = \text{pounds-mass of air per lbm-mole of oxygen}$$

The specific humidity, or water vapor to dry air mass ratio, is

$$\frac{W}{A} = \frac{m_w(18.016)}{m_a(138.2689)} \quad (7)$$

Substituting equations (2), (6), and (7) into equation (1) and rearranging the terms gives

$$m_1 = \left[ 2 + 7.67478 \frac{W}{A} \right] \frac{(m_2 + m_3 + m_6) \left( 12.011 + 1.008 \frac{y}{x} \right)}{138.2689 \left( \frac{f}{A} \right)} - 2m_2 - m_3 - m_4 - 2m_5 \quad (8)$$

For clarity, equation (8) may be rewritten using chemical symbols to represent the mole fraction for each constituent:

$$H_2O = \left[ 2 + 7.67478 \frac{W}{A} \right] \left[ \frac{(CO_2 + CO + HC) \left( 12.011 + 1.008 \frac{Y}{X} \right)}{138.2689 \left( \frac{f}{A} \right)} \right] - 2CO_2 - CO - NO - 2O_2 \quad (9)$$

Equation (9) then represents the total water vapor (humidity plus water of combustion) contained in the exhaust gas with each constituent measured on a wet basis.

Defining the water correction factor as

$$C_w = 1.0 - H_2O \quad (10)$$

we can convert the entire equation (9) to dry basis measurements by dividing by  $(1.0 - H_2O)$ :

$$\frac{H_2O}{1 - H_2O} = \left[ 2 + 7.67478 \frac{W}{A} \right] \left[ \frac{\left( CO_{2 \text{ dry}} + CO_{\text{dry}} + \frac{HC_{\text{wet}}}{1 - H_2O} \right) \left( 12.011 + 1.008 \frac{Y}{X} \right)}{138.2689 \left( \frac{f}{A} \right)} \right] - 2CO_{2 \text{ dry}} - CO_{\text{dry}} - \frac{NO_{\text{wet}}}{1 - H_2O} - 2O_{2 \text{ dry}} \quad (11)$$

where

$$CO_{2 \text{ dry}} = \frac{CO_{2 \text{ wet}}}{1 - H_2O} \text{ etc.}$$

The solution to equation (11) may be obtained iteratively by assuming a value for  $H_2O$  on the right side of the equation, solving for  $H_2O$  on the left side, using this new value for  $H_2O$  on the right side and repeating the process until satisfactory agreement has been obtained between the assumed and calculated values. Using this scheme, convergence is obtained usually within four iterations.

A more expansive chemical equilibrium calculation was made over the normal range of fuel-air ratios, considering the products of combustion to include C, Ar, CO,  $CO_2$ ,  $H_2$ ,  $H_2O$ ,  $N_2$ ,  $O_2$ , O, OH, H, NO, N,  $NH_3$ , and  $CH_4$ . The maximum error determined in the calculation of water vapor using our abbreviated product of combustion equation was less than one-half of one percent.

The solution to the wet correction factor then was obtained by using five equations ((1), (2), (6), (7), and (10)) involving five unknowns ( $m_a$ ,  $m_w$ ,  $m_l$ ,  $m_f$ , and  $C_w$ ). The assumptions made in order to effect a solution to the water correction factor are

(1) The combustion equation represents all of the elemental constituents involved in the actual combustion process.

(2) The ratio of hydrogen to carbon atoms for all 100/130 octane aviation gasolines remains constant at (y/x).

While there are similar methods which can be used to calculate the water correction factor, it is believed that this method involves the use of the least number of assumptions leading to the most accurate estimate of  $C_w$  based on the quantities currently being measured.

#### Calculation of Mass Emission Values

As mentioned previously, the raw emissions are measured on a volumetric basis in percent or ppm. In order to determine the emissions based on the requirements of the EPA Standards, these volumetric values must be converted to volumetric flow rate and then to mass flow values in accordance with

$$\begin{array}{l} \text{Pollutant} \\ \text{mass} \\ \text{emission} \\ \text{rate} \end{array} = \begin{array}{l} \text{Exhaust} \\ \text{volumetric} \\ \text{flow} \\ \text{rate} \end{array} \times \begin{array}{l} \text{Pollutant} \\ \text{volumetric} \\ \text{concentration} \end{array} \times \begin{array}{l} \text{Pollutant} \\ \text{density} \end{array} \quad (12)$$

For this equation, the pollutant densities are specified in the Federal Register at a standard pressure and temperature of 760 mm Hg and 68° F. The values of pollutant volumetric concentrations (CO, HC, NO<sub>x</sub>) are measured, and in order to calculate the mass emission rates the exhaust volumetric flow rate must be known.

The EPA Standards state that the exhaust volumetric flow rate "shall be calculated in accordance with good engineering practices."

Two methods are used by TCM to calculate the exhaust volumetric flow rate - one is called the Exhaust Volume Method and the other, the Carbon Balance Method.

The basis for the Exhaust Volume Method is in the calculation of the exhaust volumetric flow rate at the standard pressure and temperature of 760 mm Hg and 68° F using the assumption that the exhaust gas follows the ideal gas equation of state:

$$\dot{V}_{EXH} = \frac{RmT}{M_{EXH}P} = \frac{R(f + A')T}{M_{EXH}P} \quad (13)$$

where

- $\dot{V}_{\text{EXH}}$  exhaust volumetric flow rate,  $\text{ft}^3/\text{hr}$
- $R$  universal gas constant,  $1545.33 \text{ ft-lbf/lbm-mole-}^\circ\text{R}$
- $\dot{m}$  total exhaust gas mass flow (also equal to total induction mass flow of fuel and air by principle of mass conservation),  $\text{lbm/hr}$
- $T$  absolute temperature,  $528^\circ \text{ R}$  ( $68^\circ \text{ F}$ )
- $M_{\text{EXH}}$  exhaust gas molecular weight
- $P$  exhaust pressure,  $2116 \text{ lbf/ft}^2$  ( $760 \text{ mm Hg}$ )
- $f$  fuel mass flow,  $\text{lbm/hr}$
- $A'$  humid air mass flow,  $\text{lbm/hr}$

In equation (13),  $R$ ,  $T$ , and  $P$  are given values and  $\dot{m}$  is measured. The value of the exhaust gas molecular weight can be calculated from exhaust products.

$$M_{\text{EXH}} = \sum m_i M_i \quad (14)$$

where  $M_{\text{EXH}}$  is the "apparent molecular weight" of the exhaust gas.  $M_i$  is the molecular weight of each constituent and  $m_i$  is the mole fraction of each constituent which can be determined from measured concentrations and solution of equations (2) to (7). Solution of equation (14) further requires an assumption of exhaust hydrocarbon hydrogen to carbon ratio  $q/p$ . Studies have indicated, however, that extremely unreasonable values of calculated fuel-air ratio are obtained when the sum of the exhaust gas mole fractions are constrained to unity.

Therefore, the method used by TCM for estimating the exhaust gas molecular weight is based on chemical equilibrium calculations and assumes that chemical equilibrium exists among the exhaust products for a given measured fuel-air equivalence ratio. This assumption is reasonable since the major constituents which contribute to the exhaust molecular weight (e.g.,  $\text{N}_2$ ,  $\text{CO}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{CO}$ ) do not vary significantly from equilibrium predictions. The calculation of mass emissions of carbon monoxide as an example would be as follows by substituting equation (13) into equation (12):

$$\dot{m}_{\text{CO}} = \left[ \frac{R(f + A')T}{M_{\text{EXH}}P} \right] \times [\rho_{\text{CO}}] \times [\text{CO}] \quad (15)$$

Since, by the ideal gas assumption,

$$\rho_{CO} = \frac{M_{CO} P}{RT} \quad (16)$$

Substituting equation (16) into (15) yields

$$\dot{m}_{CO} = \left[ \frac{R(f + A')T}{M_{EXH}P} \right] \times \left[ \frac{M_{CO}P}{RT} \right] \times [CO]$$

or

$$\dot{m}_{CO} = \left( \frac{M_{CO}}{M_{EXH}} \right) (f + A') (CO) \quad (17)$$

where

- $\dot{m}_{CO}$  mass emission rate of CO, lbm/hr
- $M_{CO}$  molecular weight of CO, 28.011 lbm/lbm-mole
- $M_{EXH}$  exhaust gas molecular weight, lbm/lbm-mole
- $(f + A')$  total induction mass flow rate, lbm/hr
- CO wet volume fraction of CO in exhaust

The Carbon Balance Method of calculating exhaust volumetric flow rate is also used by TCM. This method provides a cross-check on the Exhaust Volume Method and is the same method used in the calculation of turbine engine emissions.

The Carbon Balance Method is believed to be the more accurate as measurement of airflow  $A$  and estimation of exhaust gas molecular weight  $M_{EXH}$  are not required. The Carbon Balance Method accounts for all the carbon atoms in the combustion equation, and by conservation of mass, the carbon introduced into the engine in the molecular form of fuel must be accounted for in the carbon-containing exhaust product molecules CO, CO<sub>2</sub>, C<sub>p</sub> H<sub>q</sub>.

As with the Exhaust Volume Method, the assumption is made that the ideal gas equation of state applies.

The derivation of the Carbon Balance Method is as follows. From equation (2), the carbon balance equation,

$$m_f = \frac{m_2 + m_3 + m_6}{x} = \frac{\text{moles of fuel}}{\text{moles of wet exhaust}}$$

The volumetric flow rate of the exhaust can then be calculated as follows:

$$\dot{V}_{EXH} = \frac{\dot{m}_{EXH}}{\rho_{EXH}} = \frac{\dot{M}_{EXH} M_{EXH}}{\rho_{EXH}} \quad (18)$$

where

$\dot{M}_{EXH}$  molar flow rate of exhaust, lbm-moles/hr

$M_{EXH}$  molecular weight of exhaust, lbm/lbm-mole

$\rho_{EXH}$  exhaust gas density, lbm/ft<sup>3</sup>

We define

$$\dot{M}_{EXH} = \frac{f}{m_f M_f} \quad (19)$$

where

$f$  mass fuel flow, lbm/hr

$M_f$  molecular weight of fuel

$m_f$  from carbon balance eq. (2), moles of fuel/moles of wet exhaust

From the ideal gas equation of state

$$\frac{M_{EXH}}{\rho_{EXH}} = \frac{RT}{P} \quad (20)$$

Substituting equations (19) and (20) into (18) gives

$$\dot{V}_{EXH} = \frac{f}{m_f M_f} \left( \frac{RT}{P} \right) \quad (21)$$

Substituting this result into equation (12) and using carbon monoxide as an example gives

$$\dot{m}_{CO} = \left[ \frac{f}{m_f M_f} \left( \frac{RT}{P} \right) \right] \times [\rho_{CO}] \times [CO] \quad (22)$$

The density of CO ( $\rho_{CO}$ ) by ideal gas consideration is

$$\rho_{co} = M_{co} \left( \frac{P}{RT} \right) \quad (23)$$

and the molecular weight of the fuel is

$$M_f = x \left( 12.011 + 1.008 \frac{y}{x} \right) \quad (24)$$

We can substitute equations (23), (24), and (2) into equation (22) to obtain

$$\dot{m}'_{co} = \frac{f M_{co} CO}{\left( 12.011 + 1.008 \frac{y}{x} \right) (HC + CO + CO_2)} \quad (25)$$

Note that the value  $x$  in equation (24) cancels with the  $x$  in equation (2) so that it is not necessary to know the molecular form of the fuel but only the H/C ratio  $y/x$ .

This method is attributable to Stivender (see SAE Paper 710604) and has the advantage of producing an exhaust volumetric flow rate calculation independent of measured air flow which is a source of some probable error in the Exhaust Volume Method. It is instructive to look at the difference between these two methods. In order to do this we can take the ratio of Carbon Balance to Exhaust Volume mass flow values for CO using equations (25) and (17):

$$\frac{\dot{m}'_{co}}{\dot{m}_{co}} = \frac{(f/A) (M_{EXH})}{\left( 12.011 + 1.008 \frac{y}{x} \right) (HC + CO + CO_2) \left( 1.0 + \frac{W}{A} + \frac{f}{A} \right)} \quad (26)$$

This indicates that any differences between the two methods ( $\dot{m}'_{co}/\dot{m}_{co} \neq 1.0$ ) are a function of fuel-air ratio and measured values of HC, CO, and  $CO_2$  (the value of  $M_{EXH}$  as used by TCM is a function of  $f/A$  only). Therefore, the ratio of these two values is a good indicator of the measurements of fuel flow, airflow, and HC, CO, and  $CO_2$ . TCM experience has shown that while this ratio is not equal to unity for most engines, a general range of values can be established for a particular engine model and operating mode.

As an example, when testing the Tiara 6-285-B engine, the ratio of  $\dot{m}'_{co}/\dot{m}_{co}$  was near 0.97 for the takeoff modes. A point was observed to have a value of this ratio of 1.33. Upon rechecking the recorded emissions data it was found that an error had been made in reading the value of  $CO_2$ .

These two methods of calculating exhaust mass emissions provide a good check on the accuracy of measured values. In addition, the Carbon Balance Method provides a convenient means for the measurement of exhaust

emissions in a field survey or flight test situation, as measured airflow is not required.

#### Calculation of Fuel-Air Ratio

The Exhaust Emissions Standards require a check on accuracy of measured data which involves the calculation of fuel-air ratio from exhaust gas constituents. This calculated fuel-air ratio must be within  $\pm 5.0$  percent of the measured fuel-air ratio in order for the test to be valid. (See Part 87.96, subparagraph (b) of the Regulation.)

An example of this method is given in the text "Internal Combustion Engines and Air Pollution" by E. F. Obert, page 353. The method is simple and reliable if the molecular form of the fuel and exhaust hydrocarbons is known, that is if we know the values  $x$ ,  $y$ ,  $p$ , and  $q$  in  $C_x H_y$  and  $C_p H_q$ .

To this point in the analysis we have scrupulously avoided assumption of these values by using equations in the form such that only the value of  $y/x$  must be known. This value has been measured and thus eliminates a possible source of error.

An alternative method for calculating fuel-air ratio has been developed by R. S. Spindt in SAE Paper 650507 which requires the use of ratios including  $y/x$ , eliminating the assumption of fuel molecular form, and avoiding the errors encountered by previous investigators.

A subsequent SAE Paper (660118) entitled "An Evaluation of Techniques for Measuring Air-Fuel Ratio" by L. C. Broering, Jr., shows that the Spindt Method is accurate to within  $\pm 5.0$  percent at a fuel-air ratio of 0.067. This conclusion, however, was based on a limited data base using an automotive engine.

The derivation of the Spindt Method will not be covered here except to say that the required input values are  $O_2$ ,  $CO$ ,  $CO_2$ ,  $HC$ ,  $y/x$ , and the assumption of the water-gas equilibrium parameter,  $K_p$ . Equation (27) is the Spindt equation:

$$\frac{f}{A} = \frac{1.0}{FB \left[ (11.492)FC \frac{1.0 + E/2 + D}{1 + E} + \frac{120(1 - FC)}{(K_p + E)} \right]} \quad (27)$$

where

$f/A$  calculated fuel-air ratio

$FB$   $(CO + CO_2)/(CO + CO_2 + HC)$

$FC$   $(12.011)/(12.011 + 1.008 y/x)$ , fraction of carbon in fuel,  $C_x H_y$



E  $\text{CO}/\text{CO}_2$

D  $\text{O}_2/\text{CO}_2$

$K_p$   $(\text{H}_2\text{O})(\text{CO})/(\text{H}_2)(\text{CO}_2)$

The water-gas equilibrium parameter comes from the chemical equation



where

$$K_p = \frac{(\text{H}_2\text{O})(\text{CO})}{(\text{H}_2)(\text{CO}_2)} \quad (29)$$

Basically, chemical equilibrium dictates through the "mass action law" that when a chemical system is in equilibrium at a constant temperature the mole fractions of the reactants ( $\text{H}_2$  and  $\text{CO}_2$ ) and products ( $\text{H}_2\text{O}$  and  $\text{CO}$ ) take on values such that the value  $K_p$  in equation (29) remains constant.

Another way to look at this phenomenon is that in equation (28) the rate of change of  $\text{H}_2 + \text{CO}_2$  into  $\text{H}_2\text{O} + \text{CO}$  is equal to the rate of change of  $\text{H}_2\text{O} + \text{CO}$  into  $\text{H}_2$  and  $\text{CO}_2$ .

The basis for this assumption in the combustion process is that as the exhaust gases expand and cool in the expansion and exhaust strokes, the rates of reaction decrease to a very small value due to the sudden decrease in temperature and the water-gas equilibrium reaction is essentially "frozen" at the higher temperature values. This assumption is invalid in that the temperatures of the exhaust gases at the start of the expansion stroke vary considerably with engine operating mode and fuel-air ratio. For the most part, at least at the higher power modes of the aircraft emissions cycle (takeoff, climb, approach), TCM has found that measured values of fuel-air ratio agree to within the required  $\pm 5.0$  percent of those calculated by the Spindt Method.

Having taken all reasonable steps necessary to assure the accuracy of the data collected from the five different engines investigated to date, the conclusion has been reached that the Spindt Method is not accurate to within  $\pm 5.0$  percent at low power modes (taxi/idle). In addition, it has been determined that the requirement that measured and calculated fuel-air ratios be within  $\pm 5.0$  percent is not sufficient to prove that the measured emissions data is accurate. A case in point is the takeoff mode data point mentioned previously where a reading error was discovered in the value of  $\text{CO}_2$  on the Tiara 6-285-B engine. The error was made evident by noting an unusual value of Carbon Balance against Exhaust Volume mass emissions data. The calculated fuel-air ratio for that data point was well within  $\pm 5.0$  percent of the measured value.

A thorough investigation of the source of error in the Spindt Method led to the discovery that the assumption of a constant value of the water-gas equilibrium parameter is in error. Spindt used a value of 3.5 as it best fit his data. Indications from TCM data show that the value of  $K_p$  may vary from 2.1 to 4.4. A specific value of the water-gas equilibrium constant may be applicable in comparing similar engine operating conditions, but in general it would not be valid to assume it as a constant for all modes of operation.

When using the Spindt Method for calculating fuel-air ratio with a constant value for  $K_p$ , it seems inappropriate to eliminate a lower power data point where calculated and measured fuel-air ratios are not within the prescribed  $\pm 5.0$  percent tolerance.

Unless another calculative procedure is developed with the promise of greater accuracy in predicting fuel-air ratios at lower power modes, it seems unlikely that the requirements of data validity can be met.

#### Exhaust Emissions Standards

Once the mass emission values of CO, HC, and NO have been determined, the calculation of exhaust emissions relative to the EPA standards (table B-2) is straightforward.

TABLE B-2. - EPA EMISSIONS REGULATIONS REQUIREMENTS

Mode	Mode name	Time in mode, min	Power, percent	Engine rpm, percent
1	Taxi/ idle-out	12.0	(a)	(a)
2	Takeoff	.3	100	(100)
3	Climb	5.0	75-100	(a)
4	Approach	6.0	40	(a)
5	Taxi/ idle-in	4.0	(a)	(a)
Total cycle		27.3	---	---

<sup>a</sup>Manufacturer's recommendation.

This table shows the required five-mode LTO cycle. In each mode, run consecutively, the mass emissions are calculated in lbm/mode. The sum of these values, lbm/cycle, is then divided by the engine rated brake horsepower so that the final emissions values are given in lbm/bhp/cycle. The Standards specify as maximum allowable values: CO, 0.042 lbm/bhp/cycle; HC, 0.0019 lbm/bhp/cycle; NO<sub>x</sub>, 0.0015 lbm/bhp/cycle.

## TCM Emissions Measurement System Modifications

Date: 9/3/74 to 10/25/74.

Problem: Loss of sample flow due to interaction of 3 analyzer pumps being connected to common suction line.

Correction: Balancing valves and surge chambers fitted to improve this condition.

Problem: Strip chart recorders out of calibration with no means of calibrating.

Correction: Instrumentation designed and constructed for 6 channels incorporating a standard cell for calibrating 0 - 1 mV scale.

Problem: No means of measuring sample flow response and residence times.

Correction: Event markers and chart speed switching installed on each strip chart recorder.

Date: 12/2/74 to 2/10/75.

Problem: Exhaust sample residence time excessively slow.

Correction: Two 20-foot heated lines from exhaust sampling pipe to analyzers provided by Scott. One of these removed to agree with the EPA Federal Register (issue July 17, 1973, p. 19099, Sec. 87.93). Rewiring and plumbing effected to maintain a temperature in this line of 310° F.

Problem: Standby sampling of cell air in cold weather caused the temperature of the 20-foot heated line to drop.

Correction: Heater installed in the standby air inlet with control hardware to maintain inlet air at 310° F.

Problem: Difficulty in calibrating analyzers when only one span gas per analyzer available.

Correction: Fourteen additional gases purchased and connected into the system with appropriate changeover valves for calibrating 25, 50, 75, and 100 percent of instrument scales.

Problem: No means of measuring sample air on input to induction air system.

Correction: Sample line and filter installed with necessary change-over valves and fittings as requested by NAFEC.

Date: 5/6/75 to 6/26/75.

Problem: Sample lines to NO<sub>x</sub> analyzer and dryer unit in main console not heated causing moisture problems.

Correction: Heating apparatus installed to maintain sample lines at 180° F.

Problem: Sample flow not being maintained when sampling exhaust gas. Insufficient capacity of pumps to overcome restriction of line heated filter due to exhaust contaminants.

Correction: Higher capacity pump installed in the downstream end of the 20-foot heated line. This gave only a partial correction to problem.

Date: 10/20/75 to 11/26/75

Problem: Sample flow still unstable.

Correction: All pumps replaced by one master pump situated near exhaust sampling pipe at upstream end of 20-foot heated line. Excess sample gas relief valve installed downstream of 20-foot heated line with flow gage. This has effectively stabilized flow rates.

Problem: CO and CO<sub>2</sub> flow gages hard to read at required flow rate of 3.0 CFH.

Correction: 24 CFH gages replaced with 5 CFH gages.

#### TCM 215 HC Analyzer Modifications

Date: 10/14/74 to 10/21/74.

Problem: Detector bench temperature exhibits lack of control (i.e.,  $\pm 6^{\circ}$  F).

Correction: Control updated by Scott to control within  $\pm 2^{\circ}$  F.

Date: 12/2/74 to 12/20/74.

Problem: HC sample pump (MB21) gave insufficient sample flow (i.e., 3 CFH max.).

Correction: Higher capacity pump (MB115) fitted to give 10.5 CFH.

Date: 5/6/75 to 6/26/75.

Problem: HC analyzer calibration nonlinear on 50 K and 100 K ranges.

Correction: Fine wire inserted into detector capillary tube to reduce flow rate.

Problem: Restriction to flow caused by vapor condensing in HC sampling tubes and flowmeter downstream of detector.

Correction: Interior temperature of HC analyzer raised from 80° to 120° F by disconnecting fan, closing all vents, and insulating flowmeter from front panel.

Problem: Particles getting into system and partially blocking detector capillary tube.

Correction: Heated filter (310° F) installed in input to HC analyzer.

#### TCM NO<sub>x</sub> Analyzer Modifications

Date: 9/3/74 to 10/25/74.

Problem: Cannot maintain Scott 325 analyzer sample flow rates.

Correction: Changed sample pump from MB21 to Model MB41.

Problem: All NO<sub>x</sub> measurements measured dry as per design of equipment.

Correction: Scott 325 was replaced with a Beckman 951 (unheated analyzer). Sample lines to the 951 heated and pipe work rerouted to bypass dryer.

Date: 12/2/74 to 2/15/75.

Problem: Beckman 951 (unheated version) giving low readings of NO<sub>x</sub>.

Correction: Replaced 951 with Model 951H.

Date: 5/6/75 to 6/26/75.

Problem: 951H exhibiting a progressively reduced readout due to moisture entering the reaction chamber.

Correction: Temperature of reaction chamber raised from approximately 80° to 110° F by disconnecting heat control fan and insulating reaction chamber. Thermocouple was installed to record temperature.

Problem: NO<sub>2</sub> could not be measured because of pressure difference at input of reaction chamber when switching from converter to bypass of converter.

Correction: Balance valve which consisted of crude clamp pinching the tube gave unstable results and was replaced with needle valve and pressure gage connected to the capillary tube.

Date: 12/18/75 to 1/12/76.

Problem: Instrument could not be calibrated. Reaction chamber was starved of ozone. Ozonator Teflon lamphousing was cracked and capillary tube to ozonator was partially blocked due to distortion of Teflon tubing.

Correction: Lamphousing was replaced and capillary tubing was replaced with needle valve. Beckman has advised replacing Teflon housing every 6 months.

Ozone, which reacts with impure Teflon, is normally always present even when the analyzer is not in use as there is no provision in the instrument for purging.

Capability of purging the ozonator with nitrogen has been installed and is now a routine procedure.

Problem: Instrument calibration was nonlinear at high values of span gas. Reaction chamber flow rates had changed from 693 cc/min to 500 cc/min, due to the capillary tube becoming partially restricted.

Correction: Reaction chamber capillary tubing was replaced with a 1/8-inch tube and a needle valve.

Problem: There was a zeroing problem - the 951H unlike the 951 had no provision for feeding in zero gas. Zero point adjusted when the oxygen is turned off. This gives a zero point somewhat lower than when using a zero gas.

Correction: Solenoid valve with tubing and switching was installed to allow zero gas to be introduced into the analyzer.

Date: 6/22/76 to 7/26/76.

Problem: Sent instrument to Beckman to be modified free of charge with promised return of 1 week. After modification, Beckman found problem with noise signal on output due to faulty photomultiplier tube. Tube was replaced at TCM expense. Upon return the unit was found to have water vapor condensation internally - a problem which had not existed before sending the unit.